

Soft lithography replication of polymeric microring optical resonators

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Abstract: We have developed a soft lithography method to replicate polymeric integrated optical devices. In this method, the master device and the molded replica are made of the same materials, allowing direct comparison. To evaluate the quality of the replication, microring optical resonators are chosen as test devices because of their sensitivity to small fabrication errors. The master devices are precisely fabricated using direct electron beam lithography. The replicas are produced by the molding technique and subsequent ultraviolet curing. Compared with the master devices, the molded devices show minimal change in both physical shape and optical performance. This correspondence indicates the merits of soft lithographic methods for fabrication of precision integrated optical devices.

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1. Introduction

Semiconductor and inorganic materials have been extensively investigated and developed during the past two decades to meet the demands of high-speed telecommunications and large-scale integrated optical circuits. These materials still dominate in commercial optical devices at present. Recently, however, more attention has been paid to polymeric materials because their optical properties can be easily tuned either by molecular structure design or by doping with other functional materials. Furthermore, polymers can be easily processed and show excellent mechanical properties including good flexibility for special purposes. Finally, polymeric optical resins have been shown to exhibit very low optical loss required for commercially viable devices [1, 2].

Among integrated optical circuits, the microring optical resonator is a key device for optical communications. Due to the resonant nature of microrings, light of certain wavelengths can be cancelled by interference, resulting in periodic notches of the transmission spectrum [3, 4, 5, 6]. There are several reports of polymeric microring resonators. The typical fabrication procedure uses reactive ion etching (RIE) [7] to form the guiding structures, similar to the fabrication methods of semiconductors. A potential disadvantage of RIE for polymeric devices is that waveguide scattering loss can be significantly increased due to dry etching processes. An alternative method for making polymeric microrings is an imprinting technique in which the polymer reflows, at high temperature, and fills a hard mold with "negative" relief features [8]. However, this method also requires complicated etching processes to get a proper mold.

Soft lithography, which uses a elastomeric mold to shape soft materials, has been recently developed as a tool for micro- and nano-fabrication [9, 10, 11, 12]. Although dimensions below 10 nm can be obtained, in principle, the properties of the materials (PDMS and polymeric waveguide materials) provide that the limit of the molding technique should be at the molecular level, i.e. on the order of 1 nm [13]. Poly(di-methylsiloxane) (PDMS) is usually used to make the mechanically flexible molds because its relatively low surface energy results in weak adhesion to other materials. This property allows a large number of PDMS molds to be produced from one master device. It also allows for the easy release of the molded polymeric replicas from the PDMS mold without damage. Using soft lithography, several simple optoelectronic components have been fabricated, such as distributed feedback structures [14, 15, 16, 17], photonic band-gap structures [18, 19], microlens arrays [20], and waveguides [21, 22]. Although

soft lithography has been widely used to make such micro-structures and rudimentary optical components, here we evaluate the replication ability of this technique for polymeric integrated optical devices. In this paper, we report the comparison of a master microring optical resonator device made by electron beam lithography to the replicated devices made by soft lithography, using the same materials. The results show that soft lithography meets the rigorous requirements of high-precision fabrication for integrated optical devices.

2. Fabrication and measurement

Figure 1 is the flowchart of fabrication processes we have used in this paper. Briefly, we make the master devices by electron beam lithography and replicate them using a PDMS mold to form the devices in the same materials as the master. The substrates are silicon wafers covered

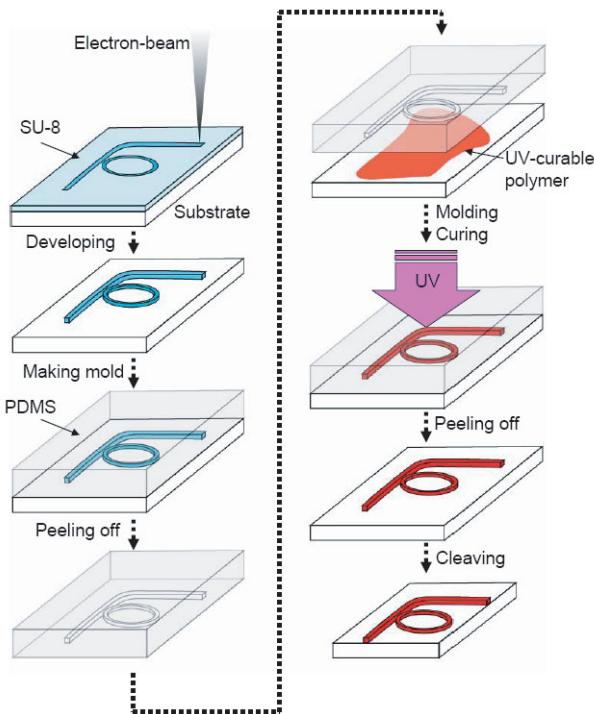


Fig. 1. Schematic diagram of fabrication processes. Generally, the UV curable polymer can be either the same material used for electron beam lithography or different ones.

with a $5 \mu\text{m}$ thermally grown amorphous silica film (refractive index 1.445). A thin film ($2 \mu\text{m}$) of negative, epoxy-type electron beam resist SU-8 (refractive index 1.565) is spin coated on the substrates and exposed by electron beam lithography to form the master device. After developing in SU-8 developer, the structure is covered by PDMS and baked at 80°C for 1 h. Once cured, the PDMS mold is peeled off. To mold the replicas, a drop of SU-8 is placed onto a new silica substrate and stamped with PDMS mold. The replicated device is cured under UV light until solidified. Both the master and replicated devices are cleaved to expose the waveguide end-facets for optical measurement.

The measurement setup is shown in Fig. 2. Light from a tunable laser is coupled into one

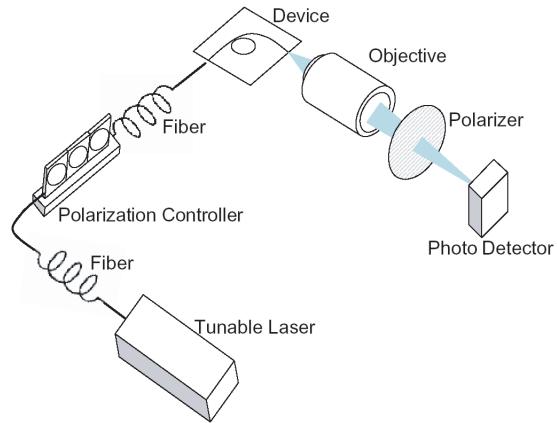


Fig. 2. Optical setup for transmission measurement.

end of the straight waveguide using a tapered fiber (also see Fig. 3). The transmission signal, collected by an objective from the other end facet of the device, is measured using a femtowatt infrared photoreceiver.

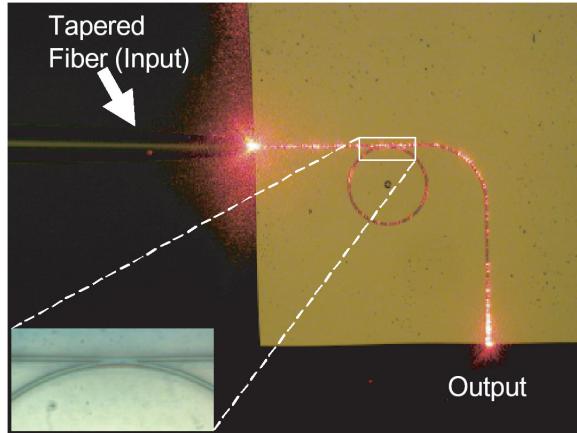


Fig. 3. Optical microscope image of microring optical resonator fabricated by soft lithography. The inset shows the detail of coupling region. The ring diameter is $200 \mu\text{m}$, the waveguide width is $2\mu\text{m}$, and the gap between the straight waveguide and the microring is 250 nm . Light from a He-Ne laser is input into the device for illustration only.

Both master devices (fabricated by electron beam lithography) and molded devices (by soft lithography) are tested under the same conditions. Figure 3 shows that the PDMS mold can successfully reproduce the details of master devices and transfer to molded ones.

3. Results and discussion

The generic geometry of a microring optical resonator is illustrated in Fig. 4. The evanescent coupling of light between the waveguide and the ring is analyzed by well-known coupled mode

theory [3, 4]. The coupling is described by the matrix

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} t & \kappa \\ -\kappa^* & t^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad (1)$$

where the two constants κ and t define the coupling efficiency between the straight waveguide and the ring. Assuming the coupling is lossless, we have

$$|t|^2 + |\kappa|^2 = 1. \quad (2)$$

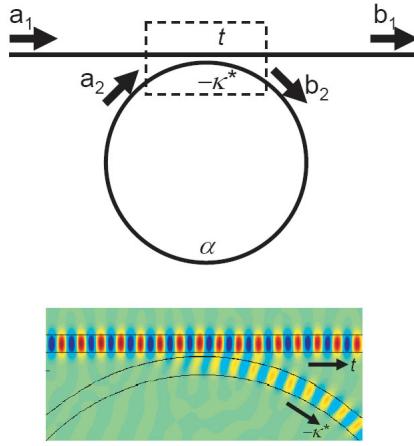


Fig. 4. Schematic geometry for waveguide ring resonator coupling. The color plot is a finite-difference time-domain simulation of the coupling between the straight waveguide and the ring.

The transmission function of microring is described by $a_2 = b_2 \alpha e^{i\theta}$, where α and θ are the loss and phase shift during one circulation, respectively. Hence the transmission of the device is

$$\left| \frac{b_1}{a_1} \right|^2 = \frac{\alpha^2 + |t|^2 - 2\alpha|t|\cos\theta}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos\theta}. \quad (3)$$

At resonance, i.e., $\theta = m2\pi$, m an integer, the equation above can be written as

$$\left| \frac{b_1}{a_1} \right|^2 = \frac{(\alpha - |t|)^2}{(1 - \alpha|t|)^2}. \quad (4)$$

The condition $\alpha = |t|$ results in a null of the output and is termed the *critical coupling* condition. In practice, for a given microring structure, α is determined by the material loss and the bend loss. To achieve critical coupling, the coupling (represented by t) must be tuned by varying the gap between the straight waveguide and the microring. Precise duplication of this parameter is key to good replication of the master device.

The two transmission spectra shown in Fig. 5 are attributed to the master and the molded replica devices. The data were normalized to the input power. The shapes of transmission spectra are clearly quite similar, as any finesse-spoiling surface scattering of the master device is

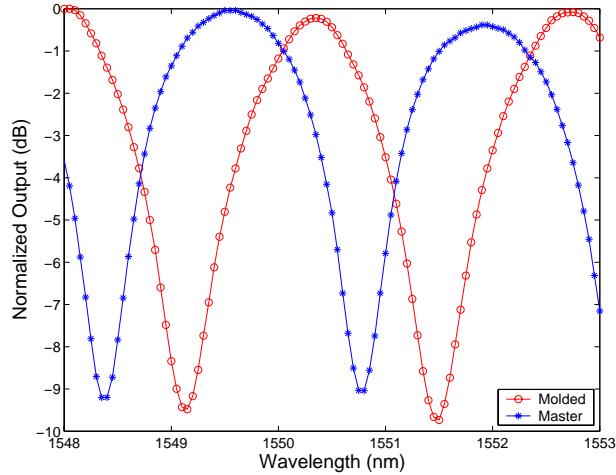


Fig. 5. Comparison between the transmission spectra of master microring resonator optical filter and molded one.

precisely reproduced in the molded device. A higher finesse master device with smoother surfaces would likewise result a higher finesse molded device. For the experiments presented in this paper, we expressly chose a lower finesse (higher loss) microresonator for demonstration purposes, since the broader spectral features would include more data points with which we could compare the two devices. The extinction of the notches, which is extremely sensitive to the coupling between the straight waveguide and the microring resonator, are almost the same ($-9 \sim -10$ dB), indicating that the soft lithography method precisely replicates the master devices on the nanometer scale. The obvious difference in the spectra of the master and molded replica devices is the shift of notch positions due to slightly different free spectral ranges (FSRs). We attribute these differences to small discrepancies between the effective refractive indexes of the two devices. The difference of effective refractive index is about 7×10^{-4} according to this measurement. In practical applications where active material is used in place of the passive core material as presented here, this shift could be controlled by applying a bias voltage.

4. Conclusion

In conclusion, microring optical resonators are fabricated by electron beam lithography and replicated by soft lithography. This fabrication technique can be applied to not only the material presented here, but to in principle, active polymer materials, such as electro-optic or luminescent polymers. Evaluating the quality of the replication, we demonstrate excellent agreement in the optical properties between molded replicated devices and master devices. This result shows the potential of soft lithography for industrialized integrated optical circuit fabrication. Compared to conventional fabrication methods currently used for polymer integrated optics, soft lithography shows promise by not only achieving the requirement of precise fabrication, but also of decreasing the fabrication cost through low material costs and high fabrication throughput.

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